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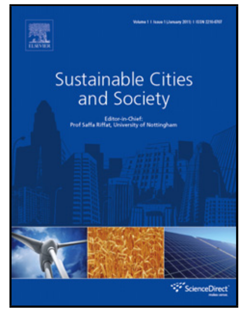
*Published in:*
Sustainable Cities and Society

*DOI:*
10.1016/j.scs.2019.101442

*Publication date:*
2019

Accepted Manuscript

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|---|---|
| PII: | S2210-6707(18)31364-7 |
| DOI: | https://doi.org/10.1016/j.scs.2019.101442 |
| Article Number: | 101442 |
| Reference: | SCS 101442 |
| To appear in: | |
| Received date: | 12 July 2018 |
| Revised date: | 15 December 2018 |
| Accepted date: | 16 January 2019 |

Please cite this article as: Alalouch C, Al-Saadi S, AlWaer H, Al-Khaled K, Energy Saving Potential for Residential Buildings in Hot Climates: The Case of Oman, *Sustainable Cities and Society* (2019), https://doi.org/10.1016/j.scs.2019.101442

# Energy Saving Potential for Residential Buildings in Hot Climates: The Case of Oman

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**HIGHLIGHTS:**

- Energy consumption of the residential sector in Oman was examined and forecasted.
- A validated simulated model of a typical Omani house was compared to an energy-efficient one in the three climatic zones of Oman using four GCC energy codes.
- Saving ranged between 13.2% to 48.2%, with UAE Estidama and Saudi Building Code achieved better saving depend on the climatic zone.
- Economic analysis show that these building codes are not always leading to economical solutions in some climates.

## ABSTRACT

This paper examines the potential of energy saving in electrical consumption if the concept of energy-efficient house is implemented in Oman. Energy consumption in the residential sector in Oman was critically analysed and forecasted based on its growth rate and its historical consumption. Then, a base-case validated simulation model for a typical residential dwelling in different cities was generated using a dynamic building simulation software, covering a wide variation of climate conditions in Oman. A variety of modified design cases that met the minimum requirements for code compliance in residential buildings for four Gulf Cooperation Council countries were developed and subsequently simulated. Then, an economic analysis was performed. The results showed that due to the high annual growth rate of the residential sector (28.5%), a considerable amount of energy (13.2% in warm tropical climate to 48% in hot dry climate) could be saved if proper building codes are put in place. Thus, this paper calls for immediate action to start a large scale programme to promote and subsequently, to enforce the use of the principles of energy-efficient house in Oman.

**KEY WORDS:** Energy-efficient house; Passive house; Building energy code; Oman; GCC countries; Energy consumption; Hot and arid climate; eQuest.

## 1. INTRODUCTION

Sustainable development is the main motivator behind the Oman National Strategic Development Plans 2020 (Alabduwani, 2010) and 2040 (Al Rahbi, 2017). Although the economical and human aspects of sustainability lie at the heart of these plans, the role of the built environment as a key component in the Omani sustainable development agenda was only recently acknowledged by the government. Nevertheless, development in this field is rather slow. This is evident through the lack of sustainability-based practices in the construction landscape in Oman. A recent study has identified six challenges associated with the implementation of sustainable construction in Oman, namely, cost effectiveness, project delays, limited availability of green materials, lack of awareness among the public, lack of trained labour and professionals, and the absence of environmental legislation (Saleh & Alalouch, 2015). In addition, the use of solar energy in Oman is limited to a number of small applications, such as street lights and parking meters (Gastli & Charabi, 2010). Furthermore, only a few projects are Leadership in Energy and Environmental Design (LEED) certified in this country (US Green Building Council, n.d.).

The move towards a sustainable built environment in Oman is timely and important due to the government policy towards diversifying the country's economy. The result has been a remarkable development in the economy, which in turn, has resulted in a rapid expansion in the building sector. The building sector is a major contributor to energy consumption and emission of greenhouse gases, with a total contribution to the global energy consumption of between 20% and 40%, exceeding other major sectors, such as transportation and industry (Pe´rez-Lombard et al., 2008). The residential sector in Oman in particular, has witnessed booming development in the last three decades. This, when combined with the on-going development in the tourism and infrastructure sectors, has created an unprecedented demand on energy.

In spite of the rapid development in this sector, current research on sustainability in Oman and the region are focused mainly on renewable energy resources and their potential in the energy production sector, and the smart grid strategy (Al-Badi et al., 2009; Kazem, 2011; Malik et al., 2018; Mohandes et al., 2019). Less attention is given to proactive procedures, such as the potential of saving in energy consumption and carbon emissions through the adoption of passive and active green strategies during the design, construction, and operation phases of new houses. If future developments in Oman and the GCC region continue in a business-as-usual mode, the built environment is likely to intensify existing problems, such as increased carbon dioxide emissions from building sector and private transport. Thus, the likelihood of costly mitigation (Stern, 2006) would increase and facilitates a decrease in wellbeing, health, and quality of life (Boyko et al., 2015).

Therefore, this paper aims to establish a business case for energy-efficient houses in Oman by providing evidence on how much energy could be saved if the minimum energy efficiency measures are put in place by the government. This paper presents an overview of the climate in Oman, and the challenges and opportunities it imposes on energy demand in the building sector. This paper also illustrates the growth rate and the consequential future growth in energy demand in the Omani residential sector. A simulation model is used to illustrate how much energy could be saved in three climatic zones in Oman, if the residential buildings are compliant with the energy efficiency requirements of building codes that exist in other GCC countries. This paper also calls for a future agenda based on improving professional practice and governmental legislations, as well as preparing the ground for more detailed research in this field. The aim is not to present definite answers or solutions, but to highlight the opportunity for energy saving in Oman and demonstrates the potential to enhance the sustainability scene in hot climate regions.

## 2. LITERATURE REVIEW

The energy saving potential in residential buildings in hot climates, if energy saving measures are put in place, is understudied. Previous studies have addressed this issue in the GCC region and the neighbouring countries by focusing on selected energy saving measures.

Taleb (2014) tested eight principal passive cooling strategies in a typical villa in Dubai, UAE using the IES energy simulation software. It was concluded that the total annual energy consumption of a residential building in Dubai could be reduced by 23.6% if proper passive cooling strategies were used. Similarly, Alaidroos and Krarti (2015) studied the effect of building envelop on energy saving in dwellings in several cities in Saudi Arabia using the EnergyPlus package. They reported that an optimal energy saving of 22.7% to 39.5% could be achieved depending on the city. In Qatar, Kharseh and Al-Khawaja (2016) studied the effects of five energy retrofitting measures of the building envelope on the cooling load in residential buildings. The energy simulation model suggested a potential 53% of energy reduction for cooling requirement when all measures were implemented, with a relatively short payback period. Meanwhile, Ameer and Krarti (2016) had focused on energy conservation codes in the Kuwaiti residential buildings. Their energy simulation-based study reported a significant reduction in energy bills when stringent energy efficiency codes were used.

Al-Saadi et al. (2017) used a calibrated energy simulation model generated by the DesignBuilder software to test different energy-efficient retrofitting strategies in residential buildings located in the hot and dry climate of Oman. Their strategies included the AC efficiency, using insulations for both walls and roof, upgrading to LED lights, and improving the air tightness of the house. The analyses showed that a total of 42.5% in energy consumption could be reduced by combining the best strategy from each measure. In contrast, another study found the maximum saving in energy to be approximately 26.7% in Oman when proper energy efficiency measures were applied (Al-Saadi & Al-Jabri, 2017). Furthermore, they reported that the optimal design for maximum energy savings were 15 cm insulation for walls and roof, a double low-emissivity selective tinted glazing, and 100 cm of overhang shading.

In a wider scale, an energy simulation model was used to investigate the effectiveness of highly reflective roofs to reduce the cooling loads of houses in Iraq (Mohamed et al., 2015). It was concluded that reflective roofs could provide a significant reduction in energy needed for cooling compared to typical roof finishes. Another study, which was also conducted in Iraq and based on the EnergyPlus simulation model, reported that using the Industrialised Building Systems in residential buildings could save the annual energy consumption up to 37.32% for heating and 65.36% for cooling (Abbood et al., 2015). Krarti and Ihm (2016) explored the cost-effective potential of designing net-zero energy residential buildings in the Middle East and North Africa (MENA) region. They found that optimal designs could cost-effectively reduce the annual energy consumption by 50% compared to the usual practices.

These studies have obtained different results in various hot climates of energy consumption saving potentials when energy efficiency measures were put in place. They also showed the lack of a clearer picture in relation to this issue in Oman. Thus, more studies are needed to understand the feasibility and impact of implementing the concept of energy-efficient house in this country. The following sections offer background information on energy consumption in the building sector with a focus on residential buildings, the concept of energy-efficient house, and building codes in the GCC countries. This paper will also describe the different climatic zones in Oman, the methodological approach adopted for this study, and the analysis results. It will conclude by discussing and reporting the findings, and proposing further considerations related to energy-efficient house in hot climates to pave the way for future researches.

### *2.1. The Building sector and energy consumption*

The building sector is one of the main energy consumers and a major contributor to carbon dioxide emissions (United Nations Environment Programme, 2009). In the United States, for example, the building sector accounted for 40% of the total energy used and corresponded to approximately 40% of carbon dioxide emissions (U.S. Department of Energy, 2010). In hot climates, these percentages would be higher due to the continuous demand for space cooling, such as in Singapore, where the building sector consumes about 57% of the entire country's power (Dong et al., 2005). In the Arab World, the building sector consumes an average of less than a quarter of the total energy consumed by all sectors. Although this average is less than the global average of energy consumed by the building sector, which is estimated to be 36%, the Arab World average is characterised by variations across countries ranging from 43% in Tunisia to 10% in Qatar (Elgendy, 2012). Since the building sector is a huge energy consumer, growth in this sector will result in higher demand for energy. According to the U.S. Department of Energy (2010), the size of the building sector is one of the main drivers behind global energy use, along with population growth and economic growth.

In Oman, the building sector has witnessed a spectacular growth due to the noticeable economic reform and the government's goal of diversifying the country's income (National Centre For Statistics & Information, 2010; National Centre For Statistics & Information, 2014). The residential sector is also expected to grow due to the socio-economic development that Oman has been experiencing in the last decades and the accelerated growth in population and income. Moreover, many young Omanis are spending more time inside buildings due to the modern life style, which suggest more energy use. The annual growth in peak energy demand in Oman is estimated to be as high as 11% (Oman Power and Procurement Company, 2014). The growth in energy consumption has increased the emission of greenhouse gases since the main power generation in Oman is dependent on fossil fuel (mainly gas and diesel).

### *2.2. The concept of Energy-efficient house*

Improved energy efficiency in the residential sector can reduce the total energy demand. This ideal, along with concern about the environment, worldwide interest in building performance, and recognising the significant impact of the residential sector on energy use, have resulted in the formulation of the Energy-Efficient House concept. Although principles of an energy-efficient building can be used in any type of building, most of the constructed low energy buildings are residential (Mekjian, 2014).

An energy-efficient house could reduce its energy consumption to a minimum by design and produces its remaining energy needs using renewable resources (Rodriguez-Ubinas et al., 2014). This concept utilises daylight, natural ventilation, shading devices and strategies, appropriate orientation on-site, optimised geometrical properties, and suitable surface-to-volume ratio in its design. An energy-efficient house would also have no or minimum thermal bridges with super thermal insulation, double- or triple-glazed windows with inert gas between panes, and air-tightness to maintain comfortable temperature all year round. It would consume minimum energy, while utilising solar power to produce its energy needs, as well as treating and recycling waste, including grey water (Alalouch et al., 2016). In addition, policy makers, architects, structural designers, energy managers, construction managers, and consultants must be involved in the development of a building if its energy efficiency is to be improved (Dakwale et al., 2011).

Although the design and construction of an energy-efficient house cost more than its business-as-usual counterparts, its running cost is lesser, thus making it economically feasible. The marriage between passive design strategies and solar power makes cost-effective cooling/heating possible. The upfront cost could increase by 2% to 7% of the total project cost (Ashrae, 2006). However, the operational cost of an energy-efficient house could be reduced, spaces could be healthier with good air quality, and productivity could increase leading to less lifecycle cost (Alwaer & Clements-Croome, 2010; Ghaffarianhoseini et al., 2018; Ghaffarianhoseini et al., 2015). Based on the financial incentives offered by many countries, the energy-efficient house makes clear economic sense.

Despite the economical, governmental, and technological barriers (Gupta et al., 2017), the concept of energy-efficient houses can be applied in any climatic zone. However, the design and construction details need be customised and optimised to meet the requirements and local conditions of the area where the house is being built. For instance, in cold zones, the aim is to improve heat recovery as most of the energy consumed in a building is for space heating. In Canada, 63% of the energy consumed in the residential sector is used for space heating, with 17% for water heating, 14% for appliances, 4% for lighting, and 2% for cooling (Natural Resources Canada, 2013). However, in very hot climate zones, such as in the Gulf Cooperation Council (GCC) member countries, energy is used mostly for space cooling. The priority is to minimise solar heat gain by using shading and proper building envelop, and maximising passive cooling through natural ventilation. In GCC countries, air conditioning counts for more than 60% of the total energy consumption (Elsarrag & Alhorr, 2012). Energy-efficient houses are mostly designed and constructed for cold regions, with the aim of reducing energy demand for space heating. Nevertheless, the principles of an energy-efficient house are being studied in hot and arid regions, such as in Oman.

### *2.3. Energy efficiency and building codes in the GCC countries.*

In Oman, architectural and structural designs are the only design documents requested by the local authority when seeking approvals for construction permit of residential buildings. The case is, however, different in other GCC countries, in which Oman is an active member. Kuwait, for example, has established an Energy Conservation Code of Practice in the early ‘80s, with recent updates, to reflect the development in the construction industry (Ministry of Electricity and

Water, 2010). The code specifies minimum requirements for energy-efficient use in all new and refurbished buildings. In an attempt to unify construction regulations in the GCC countries, the ministers of electricity recommended voluntary thermal regulations in their first meeting in 1984 (Gulf Countries Electric Energy Conservation Committee, 1984). The regulations provided minimum levels of thermal resistance (R-value) of 1.35 $m^2K/W$ for walls and 1.75 $m^2K/W$ for roofs. The same requirements were outlined in the building regulations issued by Muscat Municipality, Oman in 1992 (Muscat Municipality, 1992). In Saudi Arabia, the first building code became active in 2007 (Saudi Arabia, 2007). The code has a dedicated clause (Section 601) on energy conservation requirements for different housing typologies in different local climates. Other GCC countries, such as the United Arab Emirates (UAE) and Qatar have adopted more generic sustainability framework rating systems, where energy use is an important compliance element. In 2010, the government of Abu Dhabi in the UAE has mandated the ESTIDAMA pearl rating system for new developments. Compliance for energy use can be achieved following the energy modelling approach or the prescriptive-based design approach. The prescriptive approach is applicable to buildings with a gross floor area of 5,000 $m^2$ or less (The Department of Municipal Affairs, 2011). Meanwhile, the Qatar Sustainability Assessment System (QSAS) was developed during 2007-2010, which was later known as the Global Sustainability Assessment System (GSAS). Energy use is mainly based on performance design methodology, where the annual cooling energy use should not exceed 121 kW/h/m2 for achieving a positive score (Elsarrag & Alhorr, 2012). Table 1 summarises the minimum requirements for a residential building to comply with the prescriptive-based design approach, as described in some codes.

## 3. Climate of Oman

Oman is located in the south-eastern side of the Arabian Peninsula between latitudes 16°40’ and 26°20’ North and longitudes 51°50’ and 59°40’ East. Within its 309,500 $km^2$ border (National Centre For Statistics & Information, 2013), Oman possesses a diverse topography that includes plains, mountains, desert, valleys, and a long coastal strip line of around 3,000 km (Gastli & Charabi, 2010). The country’s capital is Muscat and the main source of economy is oil and gas revenues.

The climate in Oman is generally very hot, dry, and humid. To the authors’ best knowledge, no climate classification has been developed in Oman. The updated Köppen-Geiger map classifies Oman’s climate as BWh; a hot, dry desert climate, with the annual average temperature of higher than 18 °C (Kottek et al., 2006). This is a global classification and does not recognise the differences in Oman climate conditions nor its microclimates. Although this study has no intention of developing a full and precise climate classification for Oman, it was necessary to come up with a preliminary and rough understanding of the main climates in the country. Based on the authors' opinions and expertise, the climate of Oman can be generally classified into the following categories: warm tropical, hot humid, and hot dry. The warm tropical climate exists in the south of Oman due to the effect of the southwest monsoon, whereas the hot humid climate is located in the coastal area facing the Gulf of Oman. The rest of Oman is mostly deserts with a harsh, hot dry climate.

With the exception of the warm tropical climate, Oman has two seasons: the summer season (from May to September) is when the temperature could reach as high as 49 °C in July, with humidity of 96%; and the cool season is when the temperature ranges between 14 and 32 °C in December, with humidity ranging between 20 and 92% (National Centre For Statistics & Information, 2014). The high temperature in the long summer season often cause a high energy peak demand, which may reach its highest in July due to the need for non-stop air-conditioning (Al-Badi et al., 2009).Figure 1 shows the temperature and rainfall trends for the three climatic zones in Oman.

Oman has some of the highest solar irradiance and solar density measurements in the world (Kazem, 2011). With the average global solar radiation of 5 kWh\m$^2$\day and average duration of daily sunshine of 9.1 hours, Oman has an excellent solar potential (Al-Badi et al., 2011). Gastli and Charabi (2010) developed a GIS-based solar radiation map for Oman. The map showed very high potentials for solar energy on most of the Omani lands due to the high sky clearness index and their geographical locations. More importantly, the lack of wind and hydro resources in the GCC countries, in general, means that the majority of the renewable energy supply is likely to be sourced from solar energy.

## 4. METHODS

### *4.1. Growth rate of the Omani residential sector and its energy consumption*

This study aimed to determine the possibility of saving energy consumed by the residential sector in Oman. Hence, relevant documents published by the Omani government were surveyed and analysed to collect the required data on the size of the residential sector and its energy consumption:

- Growth rate of the residential sector: The annual growth rate of the residential sector in Oman was calculated using data published by the National Centre for Statistics and Information in their Statistical Year Book series. The first document contained information on the number of building permits issued for residential purposes for 2007 onwards.
- Energy consumption per sector: energy consumption data in Oman is managed by the Authority for Electricity Regulation (AER). AER was established by the Omani government in 2004 and their first annual report provided detailed energy consumption data per sector since 2006.

These documents were analysed, covering the period from 2007 till 2015, to calculate:

- The size of the residential sector compared to the size of other building sectors, i.e., non-residential and mixed-use.
- The average annual growth rate of the residential sector.
- The percentage of the average energy consumed by the residential sector compared to other building sectors, i.e., industrial, commercial, agriculture and fisheries, hotel/tourism, government, and the Ministry of Defence.

The total energy consumption in Oman at any given year was forecasted using Equation 1, which was developed using Pascal's Triangle (Edwards, 2002). Subsequently, energy consumed by the residential sector of up to 2040 was forecasted based on the percentage of the annual average of energy consumed by the residential sector and the total energy consumption each year. Even though forecasting could be done for any year, 2040 was selected as it aligns with the Oman National Strategic Development Plans 2040, which consider sustainability as one of the main factors for the development of the country (Al Rahbi, 2017).

$$E_n = (1 + r\%)^{n-o} \times E_o \qquad \textbf{Equation (1)}$$

where: $E_n$= total energy consumption in the target year, $r\%$ = annual growth rate of energy consumption, $n$ = the target year, $_o$ = the most recent year where the total energy consumption is known, $E_o$= total energy consumed at year $_o$.

### 4.2. *Simulation model*

Building simulation programmes are becoming common design tools and many are approved for code compliance in several countries. Several studies have analysed the utilisation of simulation tools in evaluating the energy and thermal performance of buildings. Recent simulation-based studies for high performance buildings include Friess et al. (2012), Ferrara et al. (2014), Georges et al. (2014), Sadeghifam et al. (2015), and Becchio et al. (2014). This study utilised the QUick Energy Simulation Tool (eQuest) for a yearlong simulation (Lawrence Berkeley National Laboratory, & James J.Hirsch & Associates, 1998). eQuest is a graphical user interface (GUI) from the DOE-2 (version 2.2) building energy simulation programme (eQuest, n.d.).

Other building energy simulation softwares are commercially available. Nevertheless, eQuest was chosen because it is a freeware and more importantly, it is a quick and flexible tool that allows detailed comparative analysis of building designs and technologies. This was important due to the large number of design iterations that required simulation in this study.

When comparing between eQuest and EnergyPlus, Rallapalli (2010) found that eQuest was easier to use and quick in producing results, which helped when making critical decisions during the design phase. The eQuest allows users to create multiple simulations and view the alternative results in side-by-side graphics (Crawley et al., 2008), which serves the purpose of this study. Among the hundreds of softwares in this area, eQuest was classified as among twenty major building energy simulation programmes worldwide (Crawley et al., 2008). In fact, eQuest was used in a large number of published studies related to building energy simulation. A simple search on Sciencedirect.com, using the keyword "eQuest", yielded more than 900 studies, whereby 400 of them were published between 2014 and 2018. While the researches acknowledge that no tool is perfect, eQuest was chosen for this study due to its flexibility and efficiency, which fit the nature of this study which attempts to shed light on the potential of energy saving in the residential sector in Oman.

#### 4.2.1. *Building Characteristics*

A typical residential building was assumed to be the representative house in Oman. The physical and thermal characteristics, as well as construction details commonly used in Oman are listed in Table 2.

#### 4.2.2. *Model Verification*

Building simulation programme requires many data inputs. Some of these inputs are readily available in the programme's database, while others are difficult to acquire. Experienced modellers would use their engineering judgment to overcome this challenge. Therefore, the output from these programmes will be heavily dependent on the quality and uncertainty of the inputs. To verify the results of electrical consumption in the eQuest programme, it was necessary to benchmark the simulation predictions to actual electrical consumption of residential buildings in Oman. Therefore, actual electrical consumptions of 50 residential buildings in Muscat were collected for a year (Al-Hashim, 2013). The floor plans for these particular buildings were also obtained from the Muscat Municipality. Analysis of the collected data indicated that the actual annual energy use had ranged between 53 and 199 kWh/m$^2$, with an average of 113 kWh/m$^2$. The eQuest software predicted an electrical consumption of 45 thousand kWh/year (i.e., an energy intensity of 94 kWh/m$^2$/year) for the base case building model. In addition, monthly data of energy use intensity (EUI) for eight buildings with similar floor areas were extracted from the database of fifty houses to show the seasonal variation of the EUI. The metred EUI values were compared to the simulation results, as depicted in Figure 2. The simulation results were in agreement with the average values of the metred data, which validated the model. However, the simulation result for October of that year was lower than the actual metred data because of the month of *Ramadhan*. The simulation model did not consider measurements for this month because occupants were indoors most of the time and they used more energy during this month than during other months. The base case simulation model was considered to be reliable enough for further energy analysis.

### *Energy-efficient design strategies*

To comply with the minimum requirements of the GCC energy efficiency building codes outlined in Table 1, the base case model in the eQuest software was modified as per the design cases listed in Table 3. These building codes do not meet the full potential of the concept of energy-efficient house. Nonetheless, they provide the minimum requirements for energy efficiency measures that if implemented will reduce energy consumption. They do not, for example, consider the potential of energy generation from renewable resources, which is one of the main features of the concept of the energy-efficient house. The base case and the four design cases were run for eight cities, as listed in Table 4 and shown in Figure 3, covering a wide range of climatic conditions in Oman. *Performance indicators*

To test the long-term feasibility of the design scenarios, as previously described, the technical and economic feasibilities were analysed. In this study, two performance indicators were used for the technical feasibility of the design scenarios: 1) percentage savings in annual energy consumption, and 2) percentage reduction in peak cooling load. The following Equation 2 was used to determine both indicators:

$$\%\ \text{savings in annual energy consumption or}\ \%\ \text{reduction in peak cooling load} = \frac{a - b}{a} * 100 \quad \textbf{Equation (2)}$$

where a represents either the annual energy consumption or the peak cooling load of the base case, and b represents the annual energy consumption or the peak cooling load of the new design. For the economic feasibility, two performance indicators were also used: 1) simple payback period (SPP), and 2) Life Cycle Cost (LCC). SPP was measured in years and evaluated using the following Equation 3:

$$\text{SPP} = \frac{\text{Total Investment Cost}}{\text{Annual Cost savings}} \quad \textbf{Equation (3)}$$

According to Krarti (2016), the LCC can be calculated using the following Equation 4:

$$\text{LCC} = \text{Total Investment Cost} + \frac{1-(1+d)^{-N}}{d} * \text{Annual Energy Cost} \quad \textbf{Equation (4)}$$

where d represents the discount rate in fraction, and N represents the life cycle of the building in years.

For the LCC analysis, the discount rate was assumed to be 5% for a 30-year lifetime. The capital cost of each design alternative is outlined in Table 5 (Ameer & Krarti, 2016).

The energy cost was extracted from AER annual report for 2015. For this analysis, two energy costs were used: 1) unsubsidised, and 2) subsidised. According to the AER annual report, the unsubsidised energy cost was 0.08 $/kWh. The subsidised energy cost for residential buildings was based on block tariffs, as follows:

1) 0-3,000 kWh, energy cost = 0.027 $/kWh
2) 3,001-5,000 kWh, energy cost = 0.039 $/kWh
3) 5,001-7,000 kWh, energy cost = 0.052 $/kWh

4) 7,001-10,000 kWh, energy cost = 0.065 $/kWh

5) Above 10,000 kWh, energy cost = 0.08 $/kWh

## 5. RESULTS

### *5.1. Size and growth rate of the residential sector in Oman*

Analysis of secondary data revealed that among the different building types, the residential buildings have been rapidly expanding in Oman. The 2010 Census showed that the number of housing units had increased from 430,996 units in 2003 to 551,058 units in 2010 (Ben-Hassan et al., 2010). This study had analysed the Oman Statistical Year Books from 2007 to 2015 (National Centre For Statistics & Information, 2010; 2011; 2013; 2016). The analysis showed that the growth in the building sector could mostly be accredited to the residential sector, as illustrated in Figure 4. The residential sector in Oman had 11,114 building permits issued in 2007 and 31,205 in 2015, with 28.5% of increased average annual growth rate.
This growth rate is expected to accelerate in the near future as 56.5% of the native Omani population are 25 years old and younger (National Centre For Statistics & Information, 2013), most of whom are pursuing a modern life style away from the conventional extended family living. Currently, the two-story detached house is the standard dwelling for young families in Oman.

### *5.2. Energy consumption of the residential sector in Oman*

The rapid growth in the Omani residential sector, as previously outlined, has a significant impact on energy consumption. Based on the annual reports published by the Omani Authority for Electricity Regulation, Table 6 shows that the residential sector had consumed between 55% and 47% of the total electricity supplied by the three electricity-supply systems between 2007 and 2015 (AER, 2008; 2010; 2012; 2014; 2015).

These values were notably higher than the world's average energy consumed by the residential sector, which was estimated to be 27% (Elgendy, 2012). According to the Natural Resources Canada (2013), the residential sector used 16% of the total energy produced in the country (accounting for 14% of the total greenhouse gas emissions). In the U.S., it was 22% and in the U.K., it was 28% of the total final energy used (Pe´rez-Lombard et al., 2008). Moreover, the energy consumed by an average person in oil-rich Arab countries was estimated to be three times higher than that of an average person in poorer Arab countries. In fact, an Omani individual was ranged as the fourth in the Arab World in terms of home energy consumption after Kuwait, Bahrain, and Emirates (Elgendy, 2012). Figure 5 depicts the percentage of the average energy consumed by different building sectors in Oman from 2007 to 2015.

### 5.3. *Forecasting energy consumption in the residential sector*

Equation 1 made it possible to forecast the total energy consumption at any given year. For example, energy consumption in 2020 would be 47,317,054 MWh. This was calculated based on the total energy consumption in 2013, as seen in Table 6, which was 22,790,657 MWh and the annual growth rate of 11% (Oman Power & Procurement Company, 2014). Therefore, $E_{2020} = (1 + 0.11)^{2020-2013} \times\ 22.790.657$.

Figure 6 shows the forecasted total energy consumption till 2040, as well as the energy consumption in the residential sector. By 2040, the residential sector will be demanding energy as high as 196.5 million MWh. This is an accumulation of 1,875 million MWh in 27 years, which will produce greenhouse gas emissions of approximately 1,395.3 million tonnes in Carbon Dioxide Equivalent (EPA, n.d.).

### 5.4. *The potential of Energy Saving in Omani residential sector*

Using the eQuest model, the design cases were modelled under different Omani climates. As seen in Figure 7, the savings in annual energy consumption varies from a minimum of 13.2% in a warm tropical climate for design case-1 to 48% in a hot dry climate for design case-3. Design case-2 (the Estidama design case) and design case-3 (the Saudi design case) offer great potential in reducing energy consumption among residential buildings in Oman. The GCC thermal regulations issued in 1982 offer the least annual energy savings because they simply tackle two design elements, namely, wall and roof insulations (i.e., R-values). If one may rank the most benefited climates from these design scenarios, it will be the hot dry climates (i.e., Buraimi, Sur, and Adam), followed by hot humid climates (i.e., Sohar, Muscat, and Khasab), and finally, the warm tropical climates (i.e., Salalah and Masirah). These results were expected since hot dry climates are normally more severe because of the higher temperatures compared to the other two climates, and therefore, higher annual savings are expected. The warm tropical climates are less severe because of the summer monsoon effect, and therefore, less annual savings would be achieved.

Table 7 provides a summary of minimum and maximum percentage savings in annual energy for different climates. It shows that for the warm tropical and hot humid climates, the highest percentage of saving in energy consumption can be achieved when the UAE, Abu Dhabi Estidama was used. In contrast, the Saudi Building Code achieved better saving in energy consumption in the hot dry climate.

By applying the minimum and the maximum percentages of potential energy saved on the forecasted energy consumption presented in Section 4.3, one can conclude that the energy consumed by the residential sector could be reduced from 193 million MWh in 2040 to between 139 million MWh (with 13.2% reduction) and 56.7 million MWh (with 48.2% reduction). These figures are achievable if proper energy efficiency measures are enforced in new residential buildings. A total saving of between 374 million MWh and 1,015 million MWh could be attained from 2015 to 2040. Figure 8 depicts the forecasted energy consumption in the residential sector up to 2040 for three scenarios, namely, business-as-usual, minimum saving (warm tropical climate, with GCC thermal regulation) and maximum saving (hot dry climate, with Saudi Building Code).
Since the residential sector consumes an average of 50.6% of the total energy in Oman, then energy consumption could be reduced in 2040 from 381.5 million KWh to between 274.5 million MWh and 112 million MWh, assuming that energy consumption of all other sectors remain constant. Thus, a total saving in energy consumption could be achieved between 739.1 million MWh and 2,007 million MWh, which would prevent 550.1 million to 1,493.8 million tonnes of Carbon Dioxide Equivalent from being released (EPA, n.d.).

### 5.5. *Impact on the peak cooling load*

Peak cooling load is as important as the annual energy consumption. Reduction in peak cooling load can lead to reduced equipment capacity, which subsequently, would reduce the initial capital cost of cooling equipment. Figure 9 shows the percentage of reduction in the peak cooling load for the design scenarios under different climatic conditions. The figure shows that a significant reduction in cooling capacity was achieved. The overall reduction trend was similar to the reduction observed in the annual energy consumption, as discussed in the previous section. Table 8 provides a summary of the minimum and maximum reduction percentages in peak cooling loads. Significant reduction in cooling equipment capacity was achieved for all designs, which could have a significant impact on the economic feasibility of each design scenario.

*Economic analysis*

Simple economic indexes, such as the Simple Payback Period (SPP), can provide a quick, yet rough answer to the economic feasibility of a design alternative. An SPP of less than 5 years is recommended and this threshold was used in this study. Table 9 lists the SPP for the four design scenarios. Values of a design scenario that met the specified SPP threshold are bolded, as shown in the table. The Kuwaiti design case (i.e., design case-4) offered an immediate payback to investments for all climates. Design case-1 similarly offered an immediate payback period for all cities, except Salalah, which is a city in a warm tropical climate. For this city, design case-2 and

GCC Thermal Regulations UAE, Abu Dhabi Estidama Saudi Building Code Kuwaiti Building Code

design case-3 were economically unfeasible using both energy cost scenarios (i.e., subsidised and unsubsidised). All design scenarios offered immediate paybacks to Sur, which is a city in a hot dry climate. The immediate payback period would have resulted from the significant reductions of the peak cooling load, which would subsequently lead to lower initial investment for cooling equipment compared to the base case. Design case-3 was economically unattractive under the subsidised energy cost for the majority of the cities. Prior to implementing the energy code in Oman, the authority of jurisdiction would have to be careful when using the prescriptive approach for some climates. A performance design approach should be considered as an alternative to comply with the future energy code.

Life cycle cost takes the whole life cycle of the building into consideration. This index provides more accurate data when performing economic feasibility studies. When the LCC of a design scenario is lower than the LCC of the base case, then the design scenario can be considered as feasible. Table 10 lists the LCC values for the four design scenarios. Although the LCC values varied from one climate to another, they were attractive scenarios for all climates. However, design-2 and design-3 showed higher LCC values than the base case for Salalah under the subsidised energy cost. Design-3 also has higher LCC values than the base case for the unsubsidised cost. The LCC analysis confirmed that design-3 should be carefully examined for

Salalah's climate as there is no economic benefit from adopting this design scenario. This observation was confirmed when SPP analysis was performed.

## 6. DISCUSSION AND CONCLUSION

The noticeable and rapid increase in the number of Omani households because of the continuous population and income growth on one hand, and the significantly higher energy demand by the residential sector, with the high per-person average home energy consumption on the other, call for immediate move towards energy efficient houses. Therefore, this paper examined the potential of saving in energy consumption if energy-efficiency design strategies are enforced in the newly-built Omani residential sector.

The annual growth rate of the residential sector was approximately 28.5%, and consuming as high as 50.6% of the total energy system in Oman. This percentage was significantly higher than the world's average, which was estimated to be 27% (Elgendy, 2012). A forecasting model was developed in this study based on the growth rate of this sector and its historical energy consumption. This model showed that the energy consumed by the residential sector could be as high as 193 million MWh in 2040; accumulating to 1,875 million MWh, which will release greenhouse gas emissions of about 1,395.3 million tonnes of Carbon Dioxide Equivalent into the Omani atmosphere.

A large proportion of the energy consumed for air cooling in the residential sector and the equivalent $CO_2$ emissions could be reduced if proper energy efficiency measures are adopted in newly-built housing in Oman. To test this hypothesis, a validated simulation model for a business-as-usual Omani resident was developed. This model examined the potential saving in energy when the minimum requirements for code compliance in residential buildings for four GCC countries were applied, namely, the GCC thermal regulations, the UAE, Abu Dhabi Estidama, the Saudi Building Code, and the Kuwaiti Building Code. Simulations were conducted under different cities covering different climatic conditions in Oman.

The analysis results of the simulation model suggested that a saving between 13.2% and 48.2% of energy consumed could be achieved in the Omani residential sector if the minimum energy efficiency measures are applied. The most beneficial climatic zone was the hot dry zone (potential saving of up to 48.2%), followed by the hot humid zone (potential saving of up to 39.9%). The least beneficial climatic zone was found to be the warm tropical zone, with a potential energy saving of up to 35.6%.

These findings are in line with previous researches conducted in Oman and the GCC countries. The total energy saving in the residential sector by implanting energy-efficiency measures could range between 22.7% and 53%: 42.5% in the hot and dry climatic zone in Oman (Al-Saadi et al., 2017); 26.7% in the hot and humid climatic zone in Oman (Al-Saadi & Al-Jabri, 2017); 23.6% in Dubai (Taleb, 2014); between 22.7% and 39.5% in Saudi Arabia (Alaidroos & Krarti, 2015); and 53% in Qatar (Kharseh & Al-Khawaja, 2016). International researches also support these findings. According to Emery and Kippenhan (2006), approximately 29% to 32% of the space energy consumption could be reduced in residential buildings if appropriate passive strategies are implemented. The United Nations Environmental Program (UNEP, 2009) estimated that energy consumption in both new and existing buildings can be cut by 30% to 80% if proven strategies and technologies are used, with no other sector providing such a viable opportunity to lower energy consumption.

As for the GCC building codes, it was found that the UAE, Abu Dhabi Estidama Code was the most appropriate for warm tropical and hot humid zones, whereas the Saudi Building Code could achieve the best percentage of energy saving in the hot dry zones. It is suggested that a “unified” building code for the whole of Oman might not achieve the optimum saving in energy consumption. Therefore, this paper calls for establishing a climatic classification for Oman. This is a necessary step towards developing appropriate building codes for each climatic zone to achieve the maximum possible energy saving by the residential sector.

In addition to energy savings, complying with any of the code requirements will also affect cooling equipment capacity. The results showed that reductions in peak cooling loads were significant for many climate zones, making some design scenarios more attractive from an economical aspect. Despite their technical feasibilities, simple payback period and life cycle cost analyses showed that the stringent design requirements, as per the UAE and Saudi codes, did not lead to economical solutions for some climates and/or under different energy cost scenarios. In particular, the requirements, as per the UAE and Saudi codes, should be carefully considered for

Salalah, which is a city with a warm tropical climate. A more advanced compliance approach, such as performance path, should be considered for these situations.

Although a simulation model was used in this study to assess the potential saving in energy, as a consequence of applying passive design measures in the residential sector, this model was calibrated with data from real projects. To the authors' best knowledge, measured data are yet to be available on the energy performance of energy-efficient houses in Oman, thus, making simulation a valid approach in this case. In addition, the simulation approach served the purpose of this study, which aimed to explore the potential in energy saving, to raise awareness among stakeholders, and to call for an immediate action towards improving the sustainability scene in the Omani built environment sector. Future researches should compare the results of this study with data from existing energy-efficient houses in Oman, once such data become available, and identify any performance gaps.

The design and construction of energy-efficient houses in Oman, in particular and in the GCC region, in general are still premature, thus justifying the lack of measured data in this field. Nonetheless, several initiatives have been established to implement principles of the energy-efficient house in Oman and in the GCC region, such as the SQU Ecohouse-Oman and the Baytna-Qatar (Alalouch et al., 2016). Attempts have been made to develop a framework for sustainable building construction (Alyami & Rezgui, 2012; Al-Jebouri et al., 2017), but it has yet to become a mainstream approach. The deployment of the energy-efficient culture requires a long-term plan, with an effective collaboration between all stakeholders that would guide the cultural change towards a more energy-efficient built environment in Oman.

This paper has mainly focused on evaluating the energy performance of the minimum design requirements mandated by the GCC building energy codes when implemented in a typical residential building under different climates in Oman. The energy-efficient design requirements in these codes are not optimised for minimum energy consumption or for low life cycle cost. In addition, renewable energy sources, such as solar or wind, have not been evaluated. It is expected that more savings in energy consumption could be achieved. This aspect was not studied in this work and it could be a subject of future research, along with detailed economic costs associated with deploying such design strategies.

In conclusion, this study aimed to contribute to the existing literature with analysis of energy consumption in the residential sector in Oman and forecasts of future consumption. This paper offers evidence on the likely savings in energy consumption in the residential sector if proper building codes are enforced. It has clearly demonstrated a great opportunity for energy saving and calls for immediate action to start a large-scale programme to promote and subsequently, to enforce the principles of energy-efficient house in Oman. It concludes that building energy-efficient houses in Oman is not only a need, but a sensible way forward. The significance of this paper lies in the fact that there have been limited endeavours in the field of energy efficiency in residential buildings, and the lack of information and data on the feasibility of this concept in the Omani climate zones.

## 7. FURTHER CONSIDERATIONS AND FUTURE OUTLOOK

The hard climatic characteristics of Oman create challenges for the design, construction, and operation of energy-efficient houses due to the need for continuous cooling, especially during the hot and long summer. Nevertheless, there are various opportunities for utilising solar power for energy generation: large solar power plants and smaller scale solar power units, or solar thermal collectors at individual building level (Al-Badi et al., 2009; Krarti & Dubey, 2017). While introducing large scale solar power plants requires decisions at strategic level, using solar power for energy generation and hot tap water production in residential buildings is more accessible due to the availability of such technologies and reduced prices in recent years. These technologies could pave the way for the construction of energy-efficient houses when accompanied with carefully selected passive design strategies. In the Gulf region, the reduction of electricity subsidies, the introduction of a carbon tax, and the development of residential PV market could play important roles in accelerating residential PV adoption (Mohandes et al., 2019). Meanwhile, Al-Marri et al. (2018) suggested that due to the presence of energy subsides in the GCC countries, people are not inclined to modify their energy consumption behaviour.

However, focusing on energy use in residential buildings as the solo criterion for sustainability might not fulfil the future needs of the country. To make the concept of energy-efficient house viable for Oman and the region, the architectural design of the house should consider the historical, vernacular, and social realities, as well as technological developments. An energy-efficient house that does not fulfil the occupant's needs, expectations, and preferences would fail the essence of a house design. The "liveability" of the house is a major component in any sustainable residential project.

In fact, energy-efficient housing was presented in this paper as a moving target, where there is neither a 'state-to-be-reached' nor a 'one-size-fits-all' solution. This implies creating a secure sense of long-term vitality, with sustainable thinking influencing all aspects of development, from the built form to financial, technological, economical, and social policies, as well as delivery mechanism. The authors acknowledge the fact that energy-efficient housing would not occur in a 'predetermined way'; they argue that it needs political will, responsible and well-educated professionals, and public awareness. It needs to be carefully discussed, openly debated, and centrally planned. This concept will need to be translated into real and tangible design solutions to avoid serious problems and additional costs in the future (Trained, 2011). This may move the design for energy-efficient housing debate in Oman away from 'best practice' and towards 'next practice', focusing on innovation in the design of housing and other building types. This study has addressed one issue within this debate and demonstrated that if this concept is properly deployed, a significant amount of energy could be saved.

On a wider scale, the aspirations and concerns described in this paper place upon professional bodies and individual professionals an enormous challenge: how to become more responsible and accountable for more efficient buildings. While this over-arching question is left for future endeavours to debate, it is worth mentioning that new ways of thinking about sustainable places must deviate from the deterministic conventional physical-led approach. It must consider the inter-relationship between people's lives and health with their environment. It must involve a more holistic understanding that buildings, neighbourhoods, towns, and cities are complex systems. Thus, the challenges of multi-level, multi-sectorial complexities associated with sustainable buildings must be addressed to improve sustainability and achieve the desired outcomes (Howden-Chapman, 2015). This stresses the close relationship between the built environment and its society: "*social drivers influence spatial change, leading to specific social interpretation and response*" (Madanipour, 2010, p. 134). Such approach is necessary to enhance the health, well-being, and quality of life of the occupants, and thus GHG emissions can be mitigated. Realising this goal may require a search for 'new professionalism', which must span all built environment, and planning and urban design professions, as they have interconnected and collective responsibilities, including fully appraising the desired outcomes (Cooper, 2009; Hill & Lorenz, 2011).

**ACKNOWLEDGEMENT**

The authors would like to thank Sultan Qaboos University for its continuous encouragement and support towards research activities. They would also like to thank Eng Aliya Al-Hashim for providing the data for electrical consumption of residential buildings in Oman.

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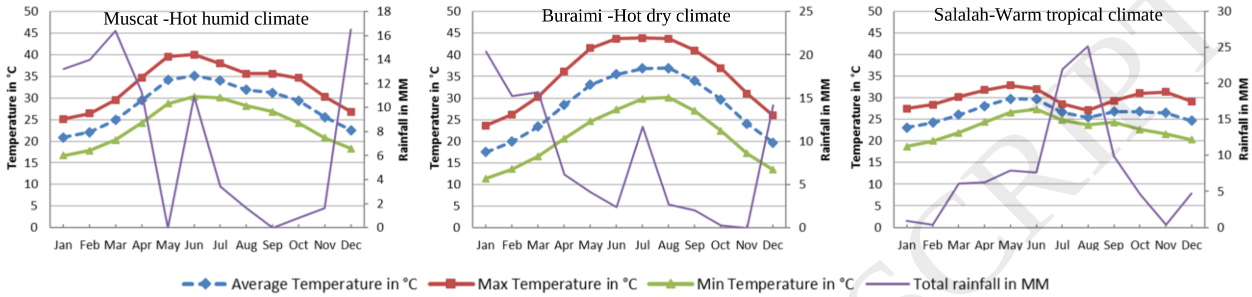


Figure 1. Yearly climatic data for the three climatic zones in Oman (world-climates, n.d.)

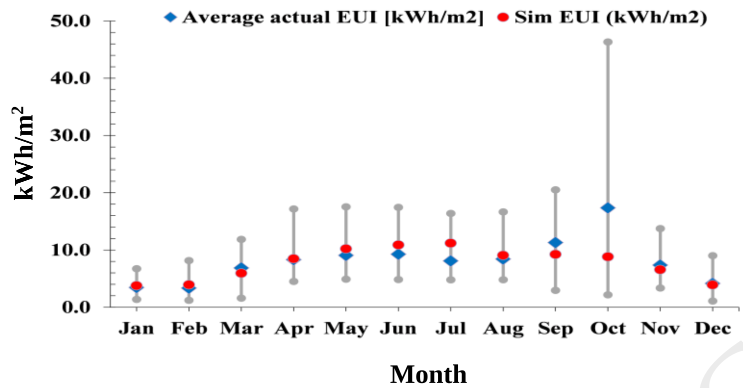


Figure 2. Actual versus simulated energy use intensity measurements for model validation

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Figure 3. A schematic representation showing the cities and their climate zones.
(Approved for Publication by the National Survey Authority, Oman- Approval No. 1221 on Dec. 12, 2018)

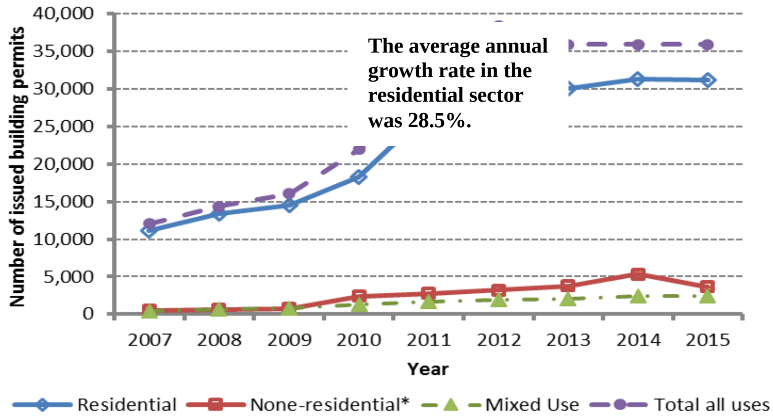


Figure 4. The number of building permits issued by the Omani government from 2007 to 2015 per building type.

* Includes: Commercial, Industrial, Tourist, Agricultural, Educational, Government, Places of worship, and Others.

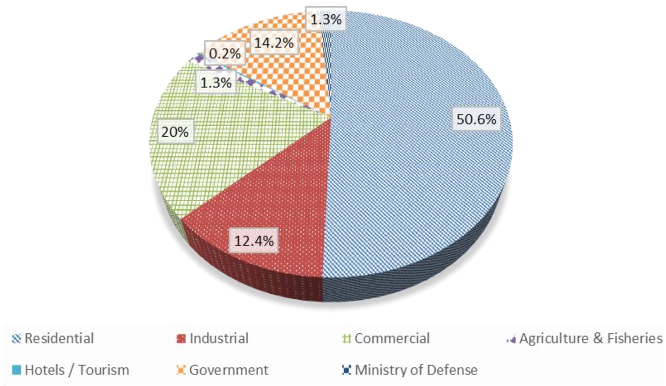


Figure 5. Average energy consumed by different building sectors from 2007 to 2015

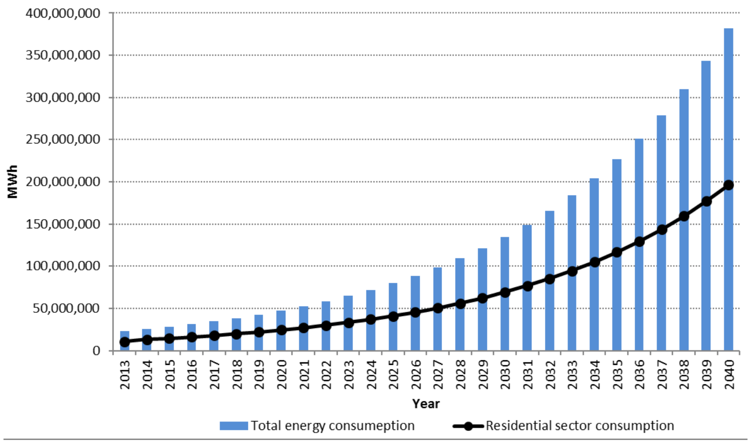


Figure 6. Forecasted energy consumption in Omani residential sector relative to total energy demand

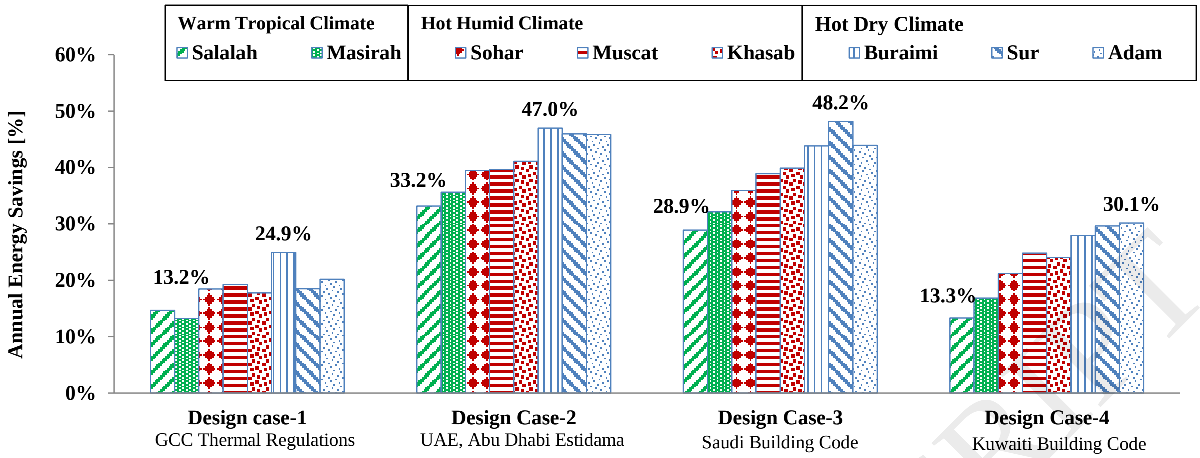


Figure 7. Annual energy savings for the four design cases under different climates of Oman

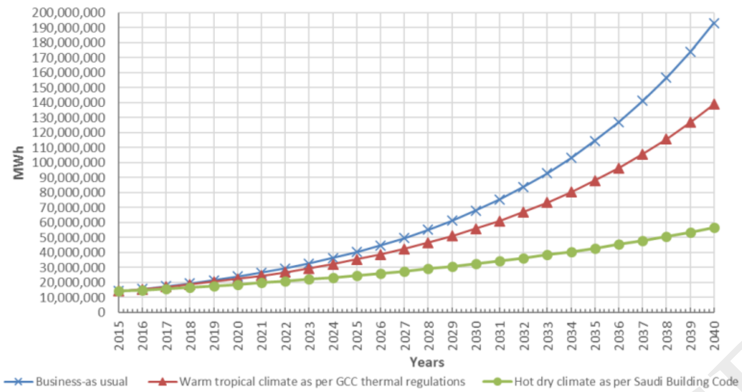


Figure 8. Forecasted scenarios of energy consumption in the residential sector up to 2040.

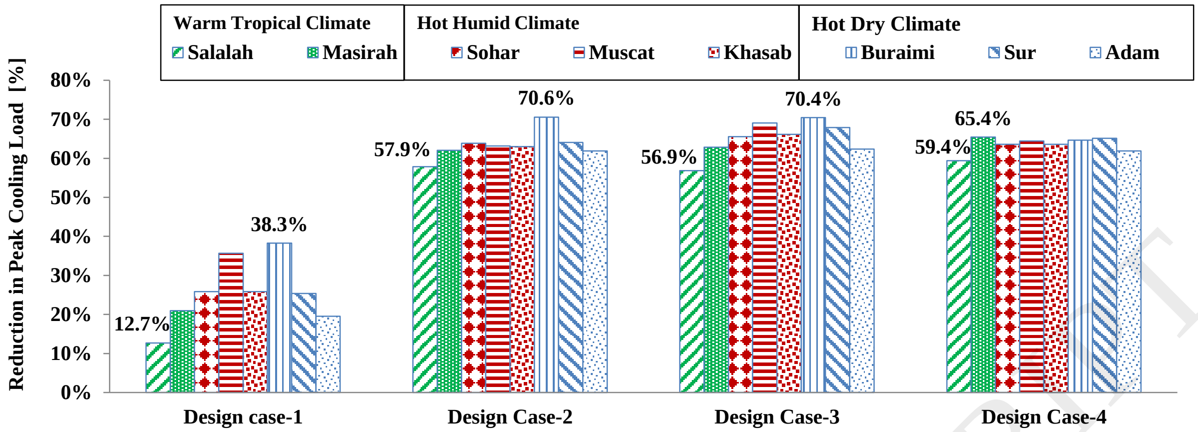


Figure 9. Reduction percentages in peak cooling load for the four design cases under different climates in Oman

Table 1. Minimum requirements for code compliance in residential buildings for different GCC countries

| **Design Element** | **GCC thermal regulations** (Gulf Countries Electric Energy Conservation Committee, 1984) | **UAE, Abu Dhabi Estidama 1 Pearl compliance** (The Department of Municipal Affairs (DMA), 2011) | **Saudi Building Code** (Saudi Arabia, 2007)** | **Kuwaiti Building Code** (Ministry of Electricity and Water, 2010) |
|---|---|---|---|---|
| Exterior Walls | U = 0.741 W/m$^2$.K (0.131 Btu/h.ft$^2$.F) | Massive wall U = 0.30 W/m$^2$.K (0.0528 Btu/h.ft$^2$.F) | Massive walls U = 0.27 W/m$^2$.K (0.0476 Btu/h.ft$^2$.F) | U = 0.483 W/m2.K (0.0851 Btu/h.ft$^2$.F) |
| Roof | U = 0.57 W/m$^2$.K (0.1 Btu/h.ft$^2$.F) | Insulation entirely above deck U = 0.2 W/m$^2$.K (0.035 Btu/(ft$^2$.hr.F)) | U = 0.116 W/m$^2$.K (0.0204 Btu/(ft$^2$.hr.F)) | U=0.341 W/m$^2$.K (0.060 Btu/h.ft$^2$.F) |
| Floor | NA | Massive floor U = 1.65 W/m$^2$.K (0.291 Btu/h.ft$^2$.F) | U = 0.27 W/m$^2$.K (0.0476 Btu/h.ft$^2$.F) | U = 0.714 W/m$^2$.K (0.126 Btu/h.ft$^2$.F) |
| Window | NA | WWR < 30% U = 1.9 W/m$^2$.K (0.335 Btu/h.ft$^2$.F) If projection factor PF < 0.25, then SHGC should be 0.23 | U = 1.99 W/m$^2$.K (0.351 Btu/h.ft$^2$.F) SHGC = 0.4 U-value of the door = 2 W/m$^2$.K (0.352 Btu/h.ft$^2$.F) | U = 3.61 W/m$^2$.K (0.636 Btu/h.ft$^2$.F) SHGC = 0.6 Tv = 0.6 |
| Infiltration | NA | 3.64 l/s/m$^2$ of exterior surface area | 0.39 (0.57 × weather factor), (Weather factor = 0.69 for hot humid climate) | 0.25 |
| Coefficient of performance (COP) | NA | If cooling capacity is > 40 kW and < 70 kW, then COP should be 3.22 | 2.7 | 2.3 |

** Requirements in Saudi Building Code are based on cooling degree days (CDD). The CDD for Muscat at 18 °C is 3849

Table 2. Characteristics of a building system for a typical residential house in Oman (Al-Saadi & Al-Jabri, 2017)

| **Characteristics** | **Description of the Base Case** |
|---|---|
| Location | Muscat, Oman |
| Orientation | Front elevation facing north |
| Plan Shape | Rectangular |
| Number of floor | Two thermal zones: living area and sleeping area |
| Floor to Floor Height | 3.35 m (11 ft) |
| Floor Area | 240 $m^2$ (2582 $ft^2$) |
| Floor Dimension | 12.5 × 19.2 m (41.5 × 62.3 ft) |
| Window Area | 15% of the gross wall area, Uniformly Distributed |
| Window | Type of Glass: 4 mm single green tinted glazing<br>Frame: Aluminium, with no thermal break |
| Solar Absorbance | 0.50 for external walls (medium colour)<br>0.50 for the roof (medium colour) |
| Exterior Walls | 15 mm cement plaster + 200 mm CMU hollow block + 15 mm cement plaster |
| Roof | Tiles + 10 mm mortar + 150 mm reinforced concrete slab + 15 mm cement plaster |
| Floors | Ground floor: 300 mm soil + 200 mm slab on grade,<br>Intermediate floor: 150 mm reinforced concrete slab |
| Shading | Interior shades when zones are occupied |
| Occupancy Density | 6 individuals |
| Lighting Power Density | 5 W/$m^2$ (for Ground and 1st Floor) |
| Equipment Power Density | 8.5 W/$m^2$ (for Ground and 1st Floor) |
| Infiltration | 0.75 ACH |
| System Type | Split air-conditioning units (Constant-Volume DX AC) |
| Thermostat Setting | 24 ºC for cooling (no heating is provided) |
| COP | 2.6 |

Table 3. Design scenarios proposed for the base case design to comply with the GCC codes

| Characteristics | Design case-1 as per GCC thermal regulations | Design Case-2 as per UAE, Abu Dhabi Estidama | Design Case-3 as per Saudi Building Code | Design Case-4 as per Kuwaiti Building Code |
|---|---|---|---|---|
| Exterior Walls | Add 3 cm of polystyrene insulation U = 0.741 W/m$^2$.K (0.1305 Btu/h.ft$^2$.F) | Add 10.4 cm of polystyrene insulation U = 0.295 W/m$^2$.K (0.052 Btu/h.ft$^2$.F) | Add 9.7 cm of polystyrene insulation U = 0.3125 W/m$^2$.K (0.055 Btu/h.ft$^2$.F) | Add 5.94 cm of polystyrene insulation U = 0.483 W/m$^2$.K (0.0851 Btu/h.ft$^2$.F) |
| Roof | Add 5 cm of polystyrene insulation U = 0.57 W/m$^2$.K (0.1 Btu/h.ft$^2$.F) | Add 16.76 cm of polystyrene insulation U = 0.2 W/m$^2$.K (0.035 Btu/h.ft$^2$.F) | Add 28.65 cm of polystyrene insulation U = 0.1163 W/m$^2$.K (0.021 Btu/h.ft$^2$.F) | Add 9.5 cm of polystyrene insulation U = 0.341 W/m$^2$.K (0.13 Btu/h.ft$^2$.F) |
| Floor | Same as base case | Add 1 cm of polystyrene insulation U = 1.54 W/m$^2$.K (0.271 Btu/h.ft$^2$.F) | Add 11.58 cm of polystyrene insulation U = 0.27 W/m$^2$.K (0.0476 Btu/h.ft$^2$.F) | Add 3.7 cm of polystyrene insulation U = 0.68 W/m$^2$.K (0.12 Btu/h.ft$^2$.F) |
| Window | Same as base case | Glazing Code: 2803* Double Electrochromic Absorbing Bleached/Coloured, 12.7 mm Gap Uwind = 1.76 W/m$^2$.K (0.31 Btu/h.ft$^2$.F), SHGC = 0.20 Frame: Aluminium, with no thermal break | Glazing Code: 2668* Double Low-E (e2 = .04) Tint Uwind = 1.87 W/m$^2$.K (0.33 Btu/h.ft$^2$.F), SHGC = 0.28 Frame: Aluminium, with no thermal break U-value of the door = 2 W/m$^2$.K (0.352 Btu/h.ft$^2$.F) | Glazing Code: 2208* Double Tint Green Uwind = 3.46 W/m$^2$.K (0.61 Btu/h.ft$^2$.F) SHGC = 0.61 Tv = 0.74 Frame: Aluminium, with no thermal break |
| Infiltration [ACH] | Same as base case | 3.64 l/s/m$^2$, which is approximately 0.35 ACH | 0.39 | 0.25 |
| COP | Same as base case | 3.22 | 2.7 | 2.3 |

* Glazing Code is based on the database in eQUEST

Table 4. Characteristics of Omani cities with different climates

| | City | Coordinates | | Climate Classification* | Weather Data Type** | CDD *** |
|---|---|---|---|---|---|---|
| | | Lat [Deg] | Long [Deg] | | | |
| 1 | Salalah | 17.03 | 54.08 | Warm Tropical | TMY | 2877 |
| 2 | Masirah | 20.67 | 58.90 | Warm Tropical | TMY | 2995 |
| 3 | Sohar | 24.47 | 56.63 | Hot Humid | TMY | 3010 |
| 4 | Muscat | 23.58 | 58.28 | Hot Humid | TMY | 3849 |
| 5 | Khasab | 26.22 | 56.23 | Hot Humid | TMY | 3667 |
| 6 | Buraimi | 24.23 | 55.78 | Hot dry | TMY | 3847 |
| 7 | Sur | 22.53 | 59.48 | Hot dry | TMY | 4070 |
| 8 | Adam | 22.38 | 57.52 | Hot dry | Measured Data ,2014 (OmanPowerandWaterProcurementCompany(OPWP), 2014) | 3908 |

* Based on Authors' opinions, ** Typical Metrological Year (TMY) from Meteonorm (Meteonorm7, 2015), *** CDD: cooling degree days calculated at 18 °C base temperature

Table 5. Total capital cost of the design alternatives (Ameer & Krarti, 2016)

| **Design Alternative** | **Total investment cost [$]** |
|---|---|
| Design case-1 as per GCC thermal regulations | 14,166.3 |
| Design Case-2 as per UAE, Abu Dhabi Estidama | 34,142.4 |
| Design Case-3 as per Saudi Building Code | 38,755.2 |
| Design Case-4 as per Kuwaiti Building Code | 21,319.7 |

Table 6. Total electricity consumed between 2007 and 2015 in Oman, as classified by building sectors

| Year | Energy consumed | Residential | Industrial | Commercial | Agriculture & Fisheries | Hotels / Tourism | Government | Ministry of Defence | Total |
|---|---|---|---|---|---|---|---|---|---|
| **2007** | **MWh** | 6,153,562 | 762,463 | 2,180,099 | 139,931 | 17,708 | 1,764,499 | 175,028 | 11,193,290 |
| | **%** | 55 | 6.8 | 19.5 | 1.3 | 0.2 | 15.8 | 1.6 | 100 |
| **2008** | **MWh** | 7,029,519 | 983,429 | 2,525,385 | 168,204 | 29,733 | 1,940,907 | 172,869 | 12,850,046 |
| | **%** | 54.7 | 7.7 | 19.7 | 1.3 | 0.2 | 15.1 | 1.3 | 100 |
| **2009** | **MWh** | 7,918,375 | 1,175,349 | 2,870,086 | 186,584 | 30,010 | 2,095,322 | 207,425 | 14,483,151 |
| | **%** | 54.7 | 8.1 | 19.8 | 1.3 | 0.2 | 14.5 | 1.4 | 100 |
| **2010** | **MWh** | 8,396,706 | 1,540,633 | 3,439,762 | 209,581 | 33,313 | 2,286,967 | 225,534 | 16,132,496 |
| | **%** | 52 | 9.5 | 21.3 | 1.3 | 0.2 | 14.2 | 1.4 | 100 |
| **2011** | **MWh** | 9,059,736 | 2,583,500 | 3,783,821 | 240,924 | 33,216 | 2,595,995 | 225,057 | 18,522,249 |
| | **%** | 48.9 | 14 | 20.4 | 1.2 | 0.2 | 14 | 1.2 | 100 |
| **2012** | **MWh** | 10,038,963 | 3,435,632 | 4,124,264 | 265,666 | 38,036 | 2,804,291 | 251,365 | 20,958,217 |
| | **%** | 47.9 | 16.4 | 19.7 | 1.3 | 0.2 | 13.4 | 1.2 | 100 |
| **2013** | **MWh** | 10,787,079 | 3,686,015 | 4,527,361 | 299,439 | 46,070 | 3,180,521 | 264,172 | 22,790,657 |
| | **%** | 47.3 | 16.2 | 19.9 | 1.3 | 0.2 | 14 | 1.2 | 100 |
| **2014** | **MWh** | 11,959,284 | 4,188,829 | 4,998,830 | 339,055 | 51,132 | 3,292,266 | 342,696 | 25,172,092 |
| | **%** | 47.5 | 16.6 | 19.9 | 1.3 | 0.2 | 13.1 | 1.4 | 100 |
| **2015** | **MWh** | 13,756,965 | 4,723,419 | 5,735,939 | 379,789 | 60,621 | 3,901,290 | 354,451 | 28,912,474 |
| | **%** | 47.6 | 16.3 | 19.8 | 1.3 | 0.2 | 13.5 | 1.2 | 100 |

Table 7. Minimum and maximum percentage of savings in annual energy for different climates

| Design Case / Climate | Range of annual energy savings [%] | | | | |
|---|---|---|---|---|---|
| | Design case-1 (GCC) | Design Case-2 (Estidama) | Design Case-3 (Saudi Code) | Design Case-4 (Kuwaiti Code) | All Design Cases (Min-Max) |
| Warm Tropical | 13.2-14.7 | 33.2-35.6 | 28.9-32.1 | 13.3-16.9 | **13.2-35.6** |
| Hot Humid | 17.8-19.2 | 39.1-41.1 | 35.9-39.9 | 21.2-24.8 | **17.8-41.1** |
| Hot Dry | 18.5-24.9 | 45.9-47.0 | 43.8-48.2 | 27.9-30.1 | **18.5-48.2** |
| All Climates (Min-Max) | **13.2-24.9** | **33.2-47.0** | **28.9-48.2** | **13.3-30.1** | |

Table 8. Minimum and maximum reduction percentages in peak cooling loads for different climates

| | Range of reduction in peak cooling load [%] | | | | |
|---|---|---|---|---|---|
| **Design Case** / **Climate** | Design case-1 (GCC) | Design Case-2 (Estidama) | Design Case-3 (Saudi Code) | Design Case-4 (Kuwaiti Code) | All Design Cases (Min-Max) |
| Warm Tropical | 12.7-21 | 57.9-62 | 56.9-62.9 | 59.4-65.4 | **12.7-65.4** |
| Hot Humid | 25.8-35.7 | 63-63.9 | 65.5-69.1 | 63.6-64.5 | **25.8-69.1** |
| Hot Dry | 19.6-38.3 | 61.9-70.6 | 62.4-70.4 | 61.9-64.7 | **19.6-70.6** |
| All Climates (Min-Max) | **12.7-38.3** | **57.9-70.6** | **56.9-70.4** | **59.4-64.7** | |

Table 9. Simple payback period for the four design scenarios for subsidised and unsubsidised energy cost

| | **Simple payback period [Years]** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Design Case** / **City** | Design case-1 (GCC) | | Design Case-2 (Estidama) | | Design Case-3 (Saudi Code) | | Design Case-4 (Kuwaiti Code) | |
| | Unsub. | Sub. | Unsub. | Sub. | Unsub. | Sub. | Unsub. | Sub |
| Salalah | 6.5 | 11.8 | 12.4 | 28.1 | 19.5 | 42.8 | **Imd.** | **Imd.** |
| Masirah | **Imd.** | **Imd.** | **2.7** | **4.9** | 6.6 | 11.4 | **Imd.** | **Imd.** |
| Sohar | **Imd.** | **Imd.** | **2.8** | **5.0** | 5.9 | 10.3 | **Imd.** | **Imd.** |
| Muscat | **Imd.** | **Imd.** | 6.5 | 11.2 | 8.5 | 14.4 | **Imd.** | **Imd.** |
| Khasab | **Imd.** | **Imd.** | **1.3** | **2.4** | **3.2** | 5.8 | **Imd.** | **Imd.** |
| Buraimi | **Imd.** | **Imd.** | **2.0** | **3.9** | **4.6** | 9 | **Imd.** | **Imd.** |
| Sur | **Imd.** | **Imd.** | **Imd.** | **Imd.** | **Imd.** | **Imd.** | **Imd.** | **Imd.** |
| Adam | **Imd.** | **Imd.** | **1.2** | **2.2** | **3.4** | 6.0 | **Imd.** | **Imd.** |

Imd.: immediate , Unsub.: Unsubsidised, Sub: Subsidised

Table 10. Life Cycle Cost for the four design scenarios for subsidised and unsubsidised energy cost

| Design Case / City | Life Cycle Cost [US $] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Base case | | Design case-1 (GCC) | | Design Case-2 (Estidama) | | Design Case-3 (Saudi Code) | | Design Case-4 (Kuwaiti Code) | |
| | Unsub. | Sub. | Unsub. | Sub. | Unsub. | Sub. | Unsub. | Sub | Unsub. | Sub |
| Salalah | 44289 | 16461 | **40540** | **15612** | **41440** | 21831 | 47728 | 26872 | **35914** | **10490** |
| Masirah | 48460 | 20077 | **40012** | **13329** | **34211** | **13552** | **39559** | **17776** | **27748** | **1358** |
| Sohar | 50914 | 21551 | **38156** | **12900** | **34459** | **14030** | **39655** | **18052** | **29665** | **3942** |
| Muscat | 54338 | 23597 | **40067** | **13011** | **41948** | **20208** | **44858** | **22857** | **35784** | **9041** |
| Khasab | 57330 | 24178 | **42982** | **15976** | **35773** | **13399** | **39190** | **16357** | **31006** | **4107** |
| Buraimi | 59239 | 24605 | **38023** | **11698** | **34983** | **14179** | **41095** | **19057** | **34310** | **7682** |
| Sur | 72824 | 32726 | **52645** | **18141** | **34316** | **8793** | **34564** | **9569** | **31017** | **1498** |
| Adam | 62512 | 27197 | **48122** | **19139** | **36125** | **13729** | **41068** | **17880** | **31574** | **5056** |

Unsub.: Unsubsidized, Sub: Subsidized